Beam Dynamics for the International Accelerator Project

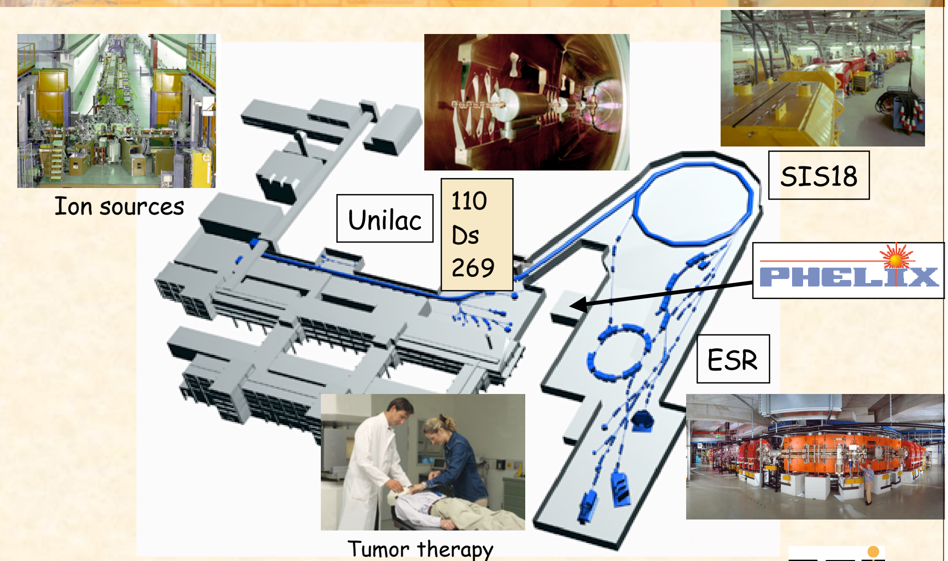
O. Boine-Frankenheim, High-Current Beam Physics, GSI, Darmstadt

Inter'l Accelerator Project

Accelerator Facility for Energetic

Ion Beams of High Intensity and Quality

The GSI Accelerator Facility



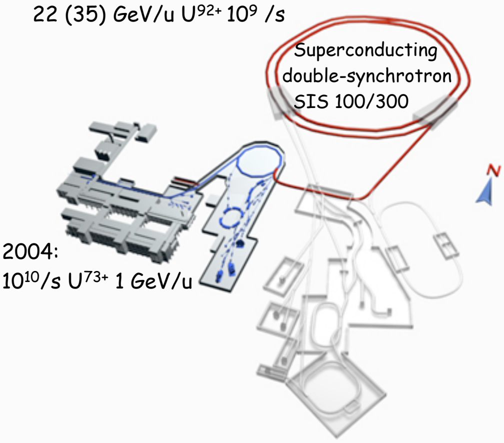
GSI

Scheme of the New Accelerator Facility

1.5 GeV/u U^{28+} 10^{12} /s

29 GeV p 10^{13} /s

22 (35) GeV/u U^{92+} 10^{9} /s



- Gain compared to the existing facility / new and special beam propoerties:
  - Primary beam intensities: Factor 100 – 1000
  - Ion energy: Factor 15 (25)

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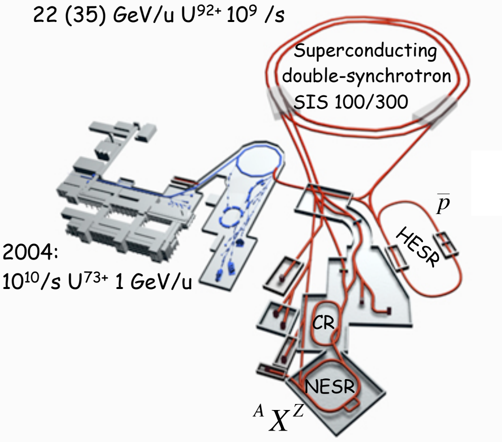

- Gain compared to the existing facility / new and special beam propoerties:
  - Primary beam intensities: Factor 100 – 1000
  - Ion energy: Factor 15 (25)
  - Secondary beam intensities for radioactive Ions: up to a factor 10000
  - New: cooled antiproton beams up to 15 GeV
  - Special: intense cooled radioactive ion beams
  - efficient parallel operation of several experiments

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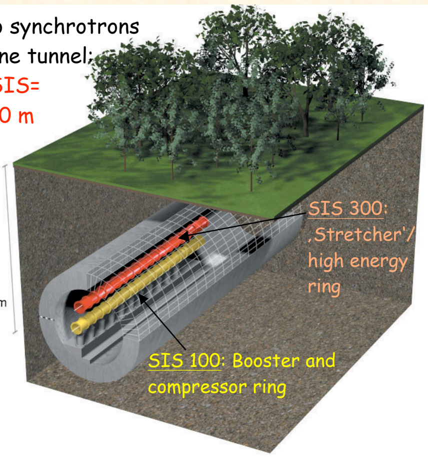
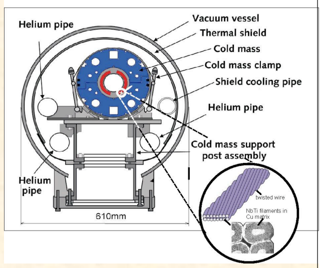
The SIS 100/300 Double-Synchrotron

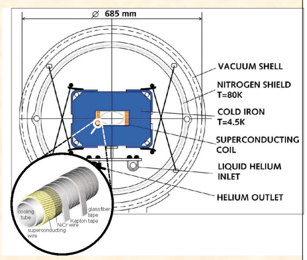
Two synchrotrons in one tunnel: 5xSIS= 1080 m



RHIC-typ dipole magnet: B=4T (6T), dB/dt=1T/s



Nuclotron-type dipole magnet: B=2T, dB/dt=4T/s



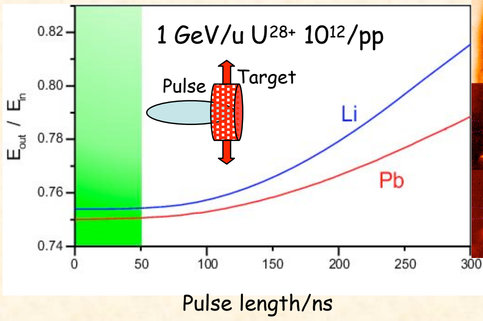
2x120 superconducting (SC) dipole magnets
132+162 SC quadrupole magnets

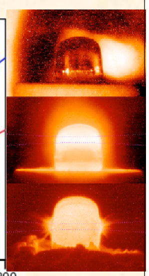
High-Power (TW) Exotic Ion Production Target

Injection of secondary beams into the collector ring (CR) requires primary Uranium beam puls length ≤ 1 μs and d≈1 mm on the target !

Problem:
Hydrodynamic expansion of the target

Solution (?):
✓Pulse length shorter 50 ns !!!
✓Target recovery with 1 Hz (liquid Lithium)





Plasma physics targets

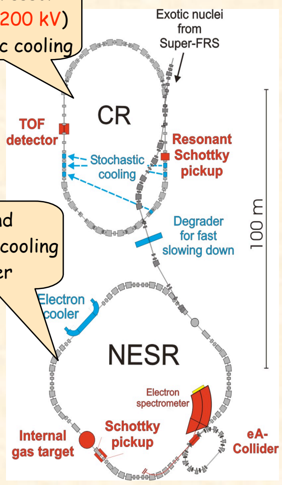
Collector and Accumulator Rings for Exotic Ions

from Target/SFRS

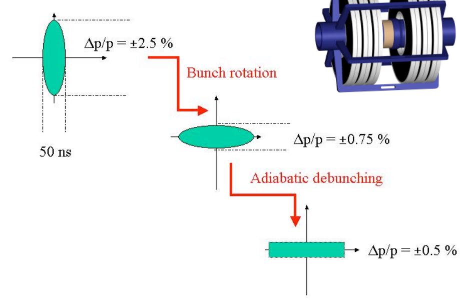
5 'decompressor' cavities (200 kV) + stochastic cooling

180 m circum- ference

Electron and stochastic cooling + eA collider



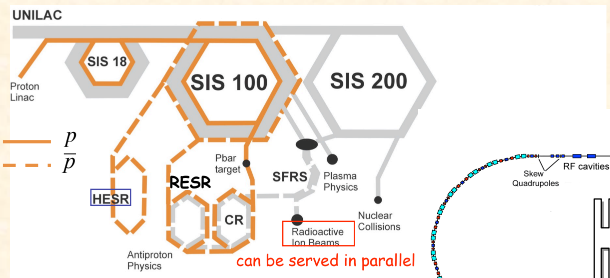
Fast debunching of exotic nuclei



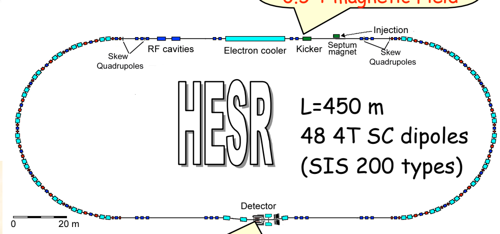
CR+NESR: 2x24 large aperture (±180 mm) superferric (1.6 T) dipole magnets

210 m circumference (approx. 2xESR)

Antiproton Generation, Accumulation and Storage



1 A, 8 MeV e-beam
30 m cooling section
0.5 T magnetic Field

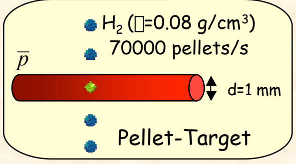


1-15 GeV $\bar{p}$

$N_{max}=10^{12}$

$L=2x10^{32}$ $cm^{-2}s^{-1}$

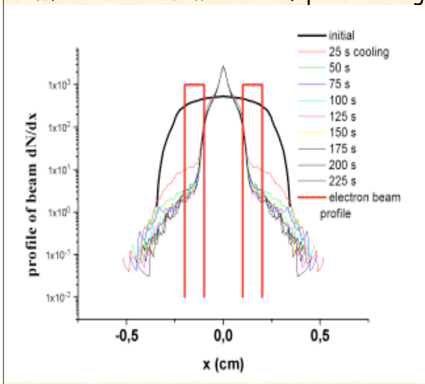
$\Delta E=100$ keV ($\Delta p/p=10^{-5}$)

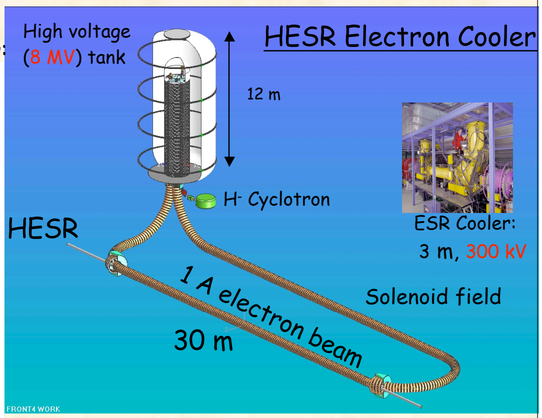


Antiproton Electron Cooling at High Energies

Feasibility study of fast ('seconds') electron cooling for the HESR, Budker Institute, Novosibirsk, RUS

Monte-Carlo-Simulation of pbar cooling:





Beam Dynamics Issues*

	low loss design	space charge	dynamic aperture	impedance budgets	intrabeam scattering	rf gym-nastics	stripping losses	e/ion cloud
SIS 18		X		X	X		X	X
SIS 100	X	X	X	X	X	X	X	X
SIS 300	X		X	X	X		X	X
CR			X			X		
RESR		X		X	X			
NESR				X	X	X		
HESR		X	X	X	X	X		X

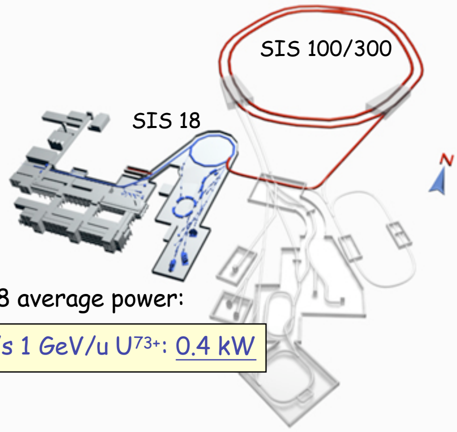
dynamic aperture: Magnet apertures and field quality, collimation concept
space charge: Apertures, collimation, feedback systems, beam quality
impedances budget: Feedback, rf + kicker design
rf gymnastics: rf requirements, beam quality
stripping + clouds: beam loss, UHV requirements
intrabeam scattering: beam quality and loss

* Linacs not covered.

SIS 100/300: Low Loss Design

SIS 100/300 average (peak) power:

10^{12}/s 2.5 GeV/u U^{28+}: 100 kW (1 TW)



SIS 18 average power:

10^{10}/s 1 GeV/u U^{73+}: 0.4 kW

Quenching/Lifetime of SC magnets:
tolerable beam loss in the SC coils: < 1 %

Structure activation:
Hands-on maintenance requires losses < 1 %

Beam loss induced outgassing

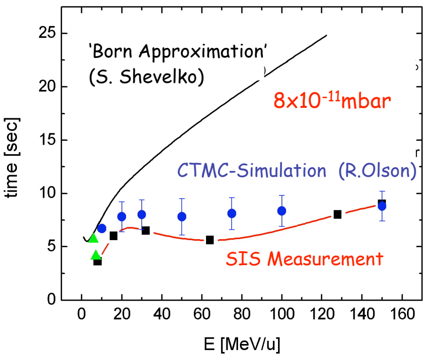
Dynamic pressure below 5×10^{-12} mbar requires < 1 %

U^{28+} Lifetime due to Stripping in the Residual Gas

Projectile-Stripping in the residual gas:

$$U^{28+} + X \rightarrow U^{(28+j)+} + X^{m+} + (m+j)e$$

U^{28+} Beam lifetime measurements in SIS:



Scaling of the stripping cross section:

$$\propto \frac{n_X}{Z_p^{1.4} E_p^{1/2}}$$

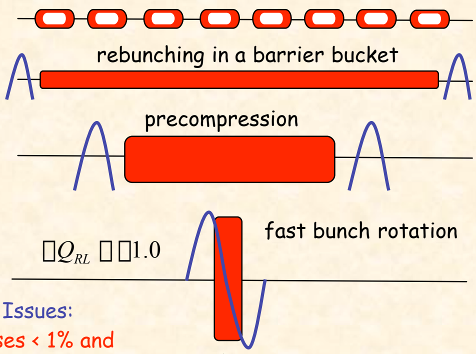
U^{28+} operation with 1 % stripping loss means:

10 s lifetime in SIS (4 Hz) or $P=5\times10^{-11}$ mbar

100 s lifetime in SIS 100/300 (T= 1 s) or $P=5\times10^{-12}$ mbar

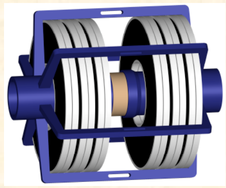
RF Bunch Manipulations in SIS 100

Injection/acceleration of (hollow) bunches in (double) rf buckets



Key Issues:
Losses < 1% and
Dilution Factor < 2 !

26 compressor cavities (20 m) filled with high-μ cores:



40 kV/m
500 kHz

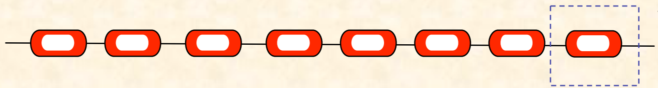
+ about 20 'normal' acceleration cavities

= 1 MV total !

10^{12} U^{28+} 1 GeV/u 50 ns ⟹ $P_{max} \approx$ 1 TW ⟹

Beam loss budget:
- Projectil range in steel ≈ 1 cm

Hollow Bunches



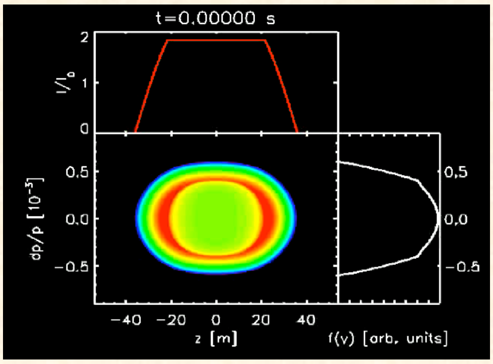
Vlasov-Fokker-Planck simulation:

$$\frac{\partial f(z,v_s,t)}{\partial t} + v_s \frac{\partial f}{\partial z} + \frac{qE_s}{m^*}\frac{\partial f}{\partial v_s} = K(v_s,f,D_{IBS})$$

$$E_s(\omega_n) = -Z(\omega_n)I(\omega_n) + E_{RF}(\omega_n)$$

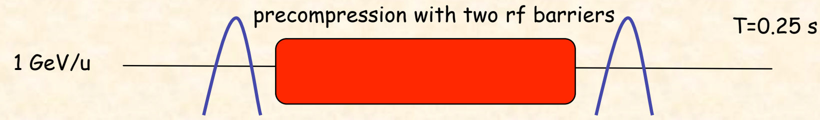
Including the following components:
- ✓Double RF voltages
- ✓Space charge impedance
- ✓RF cavity impedance
- ✓Intrabeam scattering

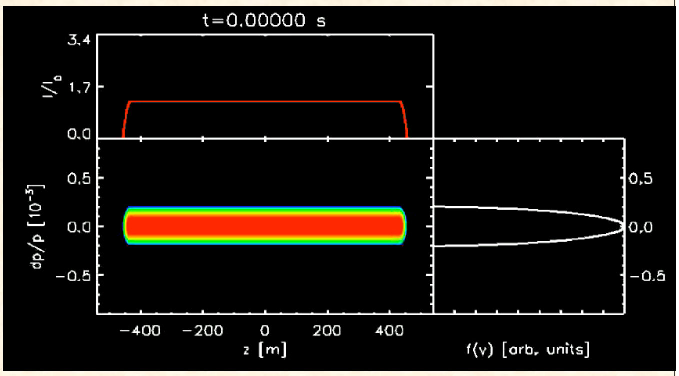
One of 8 bunches injected from SIS18:



N_z=1024, N_v=400, N_t=10^5

Moving Barriers



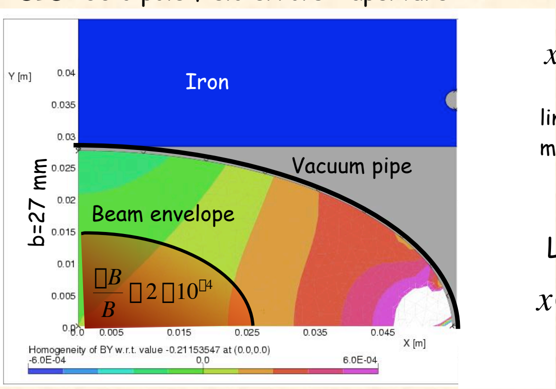


Simulation model includes:
- ✓Space charge impedance
- ✓Barrier RF + impedance
- ✓Broadband imped. (50)
- ✓Intrabeam scattering

N_z=2048, N_v=400, N_t=10^5

Nonlinear Magnet Fields and Beam Loss

SIS 100 dipole field errors + aperture:



a=55 mm

(Horizontal) betatron equation of motion:

$$x'' + k_x(s)x = \frac{\Delta B_y}{RB_0} + \frac{F_x^{sc}}{\gamma m \beta^2 c^2}$$

linear betatron motion | nonlinear magnet errors | nonlinear space charge force

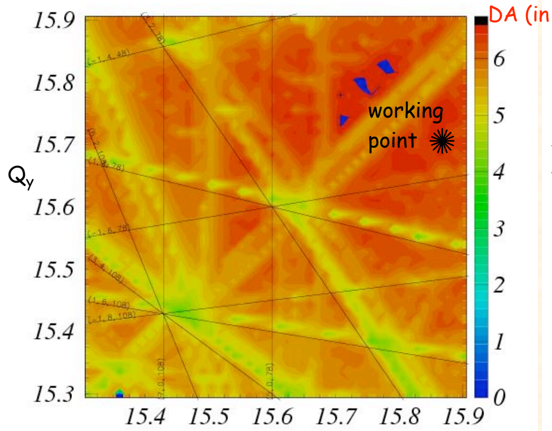
Long term stability (T=1 s):

$$x(t \le T) < a, \quad y(t \le T) < b$$

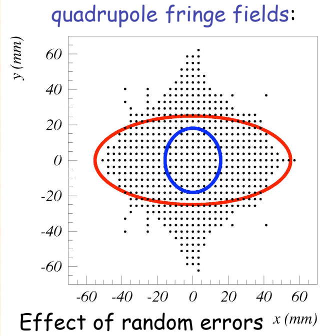
Key issue: Can we store a (thick) beam for 1 s (10^5 turns) in a nonlinear machine with space charge ?

Dynamic Aperture (no Space Charge !) in SIS 100

Dynamic aperture (DA): The boundary of the largest area inside the domain of initial particle conditions that remains stable after 10^5 turns.



Particle tracking results for systematic dipole errors and quadrupole fringe fields:



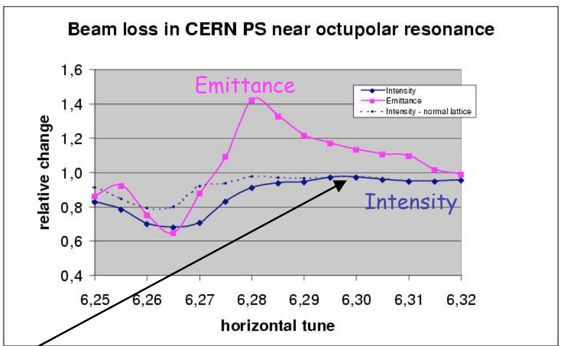
Effect of random errors is presently being studied.

G. Franchetti (2003)

New Insight into Space Charge Induced Beam Loss from a CERN PS Experiment

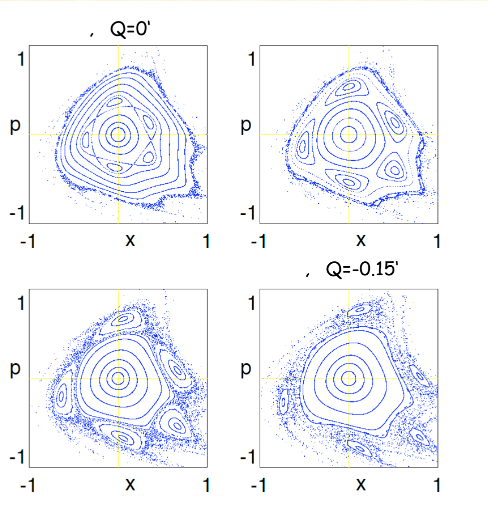
- ✓Particles trapped into moving resonance islands reach large betatron amplitudes (next slide).
- ✓The halo particles are lost at the (dynamic) aperture
- ✓3D particle tracking (10^5 turns !) ‚frozen' space charge fields reproduces experiment !
- ✓For >10^5 turns and Q=-0.15 beam loss of the order of 1-2 % seems realistic for special working point regions only !

G. Franchetti, I. Hofmann and the CERN PS team (PRSTAB 2003)

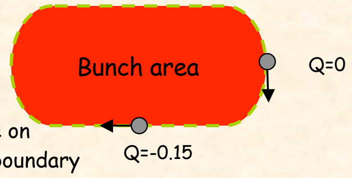


Space Charge + Island Trapping: Schematic

Transverse phase space (Henon map)



Longitudinal phase space

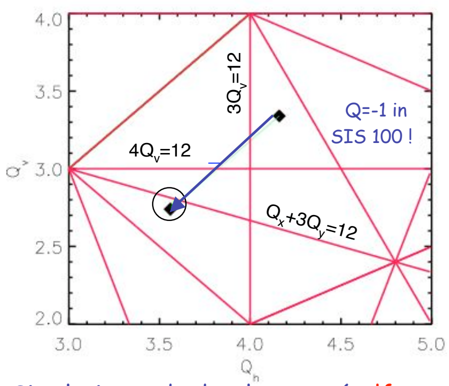


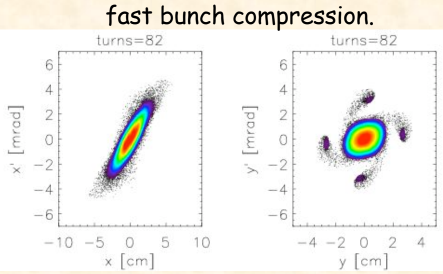
The (dynamical) aperture of SIS100/300 has to be larger than the maximum extent of the islonds !

U^{28+} Bunch compression ('single slice')

Space charge induced crossing of structure resonances in SIS during fast (100 turns) bunch compression:

2D (!) Simulation of fast bunch compression.

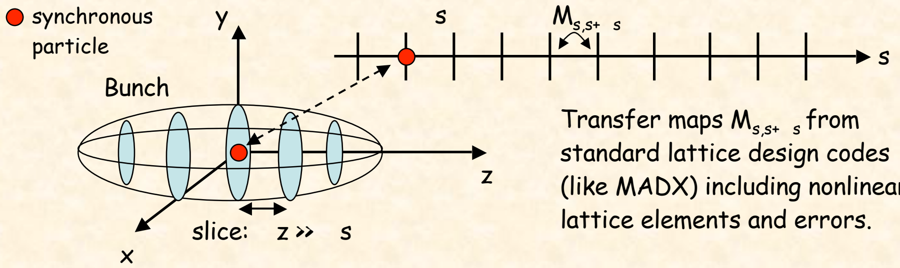




Key question:
bunch compression with losses < 1%

3D Simulation code development (self-consistent space charge) has been started !

Sliced Particle Tracking Approach



Transfer maps $M_{s,s+\Delta s}$ from standard lattice design codes (like MADX) including nonlinear lattice elements and errors.

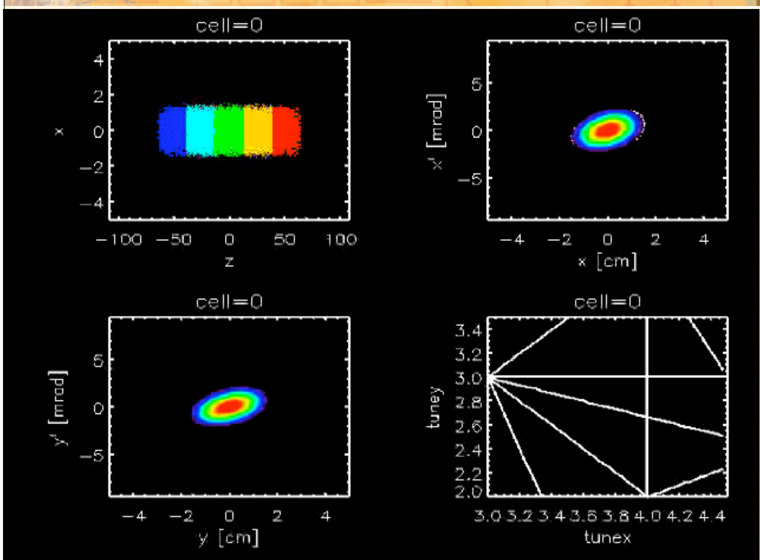
2D space charge field:

$$\frac{\partial E_x}{\partial x}+\frac{\partial E_y}{\partial y}=\frac{\rho_{\perp z}(x,y,\{z_j,s_i\})}{\varepsilon_0}$$

3D particle motion plus space charge kicks:

$$\begin{pmatrix} x \\ x' \\ y \\ y' \\ z \\ \delta \end{pmatrix}_{s+\Delta s} = M_{s,s+\Delta s}\begin{pmatrix} x \\ x' + \frac{qE_x(x,y)}{mv_0^2\gamma^3}\Delta s \\ \vdots \end{pmatrix}_s$$

Multi Slice Results



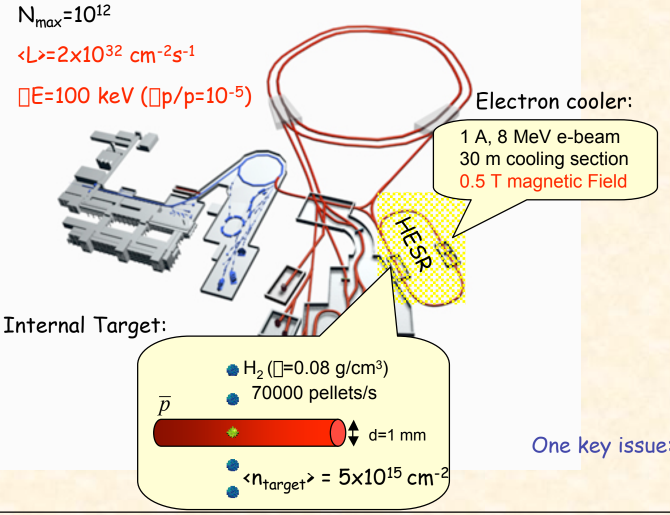
HESR: Beam Dynamics Issues

1-15 GeV $\bar{p}$

$N_{max}=10^{12}$

$\langle L \rangle = 2\times10^{32}\ cm^{-2}s^{-1}$

$\Delta E=100$ keV ($\Delta p/p=10^{-5}$)



The design of the HESR requires sophisticated beam dynamics studies, using 'frontier line' numerical computing:

computer modeling (3D) of the interplay of:

- ✓intrabeam scattering
- ✓target interaction
- ✓electron cooling
- ✓impedances/feedback
- ✓dynamic aperture
- ✓trapped particles

One key issue: Low momentum spreads + high luminosity

Antiproton Beam Equilibrium: Code Benchmarking

Boltzmann-type kinetic equation:

$$\frac{\partial f(x_i,v_i,t)}{\partial t} = K(f, v_i, \{\tau^{target}, ...\})$$

↓ 3D Gaussian distribution

Rate equations:

$$\frac{d\varepsilon_{x,y}}{dt} = (\tau^{target}_{x,y} + \tau^{IBS}_{x,y} - \tau^{cool}_{x,y})\varepsilon_{x,y}$$

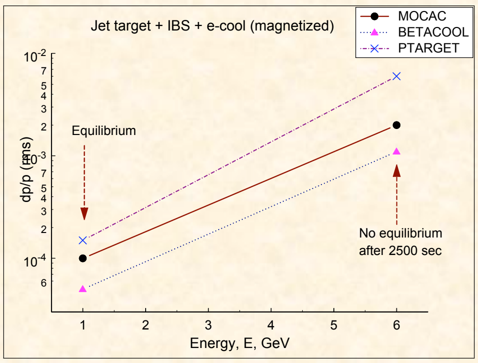
$$\frac{d(\Delta p/p)}{dt} = (\tau^{target}_{z} + \tau^{IBS}_{z} - \tau^{cool}_{z})\frac{\Delta p}{p}$$

Simulation models contain :

- ✓intrabeam scattering
- ✓target scattering
- ✓electron cooling
- ✓no self-fields !

MOCAC (ITEP): Fully kinetic
PTARGET (GSI): Partly kinetic (cooling + target)
Betacool (Dubna): Rate equations

Comparison of codes for $N=5\times10^{10}$:

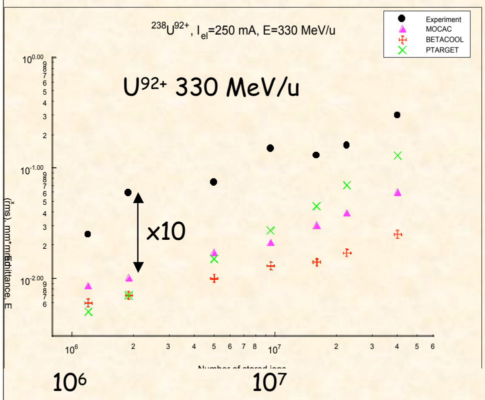


A. Dolinskii et al. (2002)

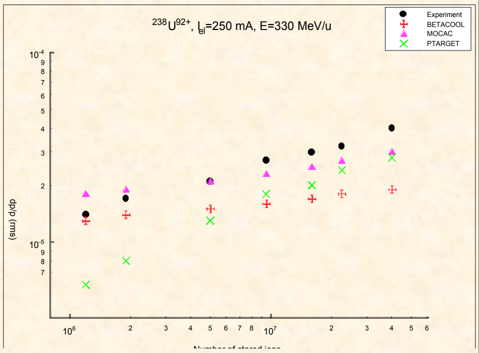
Benchmarking with Experiments

Equilibrium momentum spread in the ESR: intrabeam scattering +'magnetized' cooling

Transverse emittance vs. number of ions:



Momentum spread vs. number of ions:



'Turbulent Equilibrium'

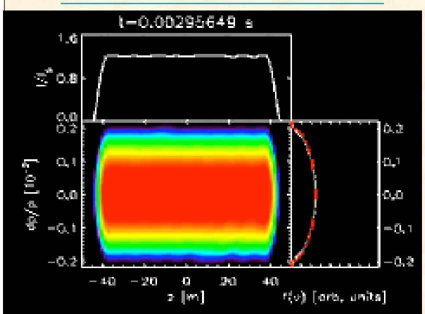
The combination of high beam current and low momentum spread might enable various (usually) undesired collective phenomena.

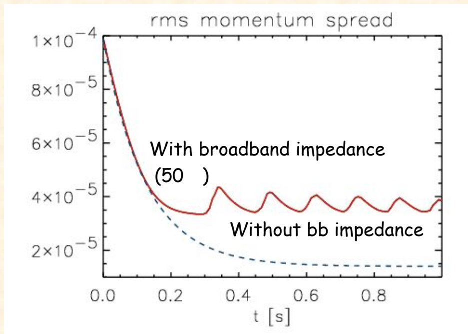
$$\frac{\partial f(z,v_s,t)}{\partial t} + v_s \frac{\partial f}{\partial z} + \frac{qE_s}{m}\frac{\partial f}{\partial v_s} = K(f, v_i, \varepsilon_{x,y}, \{F_z, D_z\}) \quad \text{(long. kinetic)}$$

$$E_s(\Omega_n) = -Z(\Omega_n)I(\Omega_n) + E_{RF} \quad \text{(long. electric field)}$$

$$\frac{d\varepsilon_{x,y}}{dt} = (\lambda^{target}_{x,y} + \lambda^{IBS}_{x,y} - \lambda^{cool}_{x,y})\varepsilon_{x,y} \quad \text{(transverse moments)}$$

Vlasov-Fokker-Planck simulation:





Key issue: control of collective effects (feedback,..)

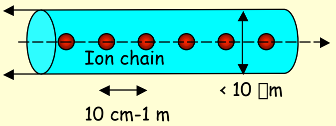
Ultra-Cold Exotic Ion Beams

Application of ultra cold beams

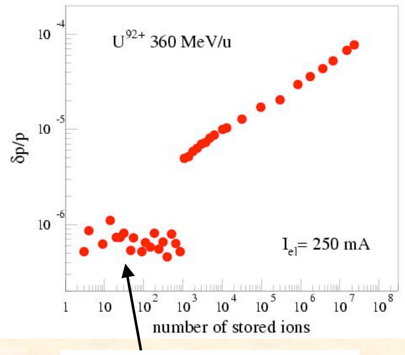
✓Today:
Mass measurements of exotic nuclei in the ESR:

$$\frac{\Delta f}{f} = -\alpha_p \frac{\Delta(m/q)}{(m/q)} \pm \left(1 - \frac{\gamma^2}{\gamma_t^2}\right)\frac{\Delta v}{v}$$

✓Tomorrow:
Highest luminosities for collider-experiments in the NESR ?



Experiments in SIS with electron cooling:



M. Steck (1996)
R.Hasse (1999)

'R&D and Simulation Challenges'

Fast ramping SC magnets:
extremly demanding

RF systems:
at the limit of technical feasibility

Control of dynamic vacuum (UHV):
at (or presently even beyond) the limit

Control of beam loss/collective effects:
extremly demanding, many open questions

Fast stochastic/electron cooling:
at the limit of technical feasibility

Longitudinal beam dynamics in RF fields
(Impedance budgets, beam quality, parameters for feedback and RF systems)

✓Simulation code development finished

Nonlinear lattice and space charge
(Magnet apertures and quality, lattice design, collimation concept)

✓3D simulation code development started

Beam cooling equilibrium
(beam quality, cooler parameters)

✓3D code development started (INTAS)

Many more ..